Processing Technology and Operations

The new turnkey CDE processing plant (*as shown in the comprehensive CDE quotation*) will include a range of equipment from the CDE product portfolio including the M4500 with integrated Counter Flow Classification Unit (CFCU), EvoWash fines recovery system with hydro-cyclones, fine sand screens, attrition cells and spirals, magnetic separators etc. The plant configuration also includes an AquaCycle thickener which reduces the volume of fresh water required to feed the washing plant by more than 90%.

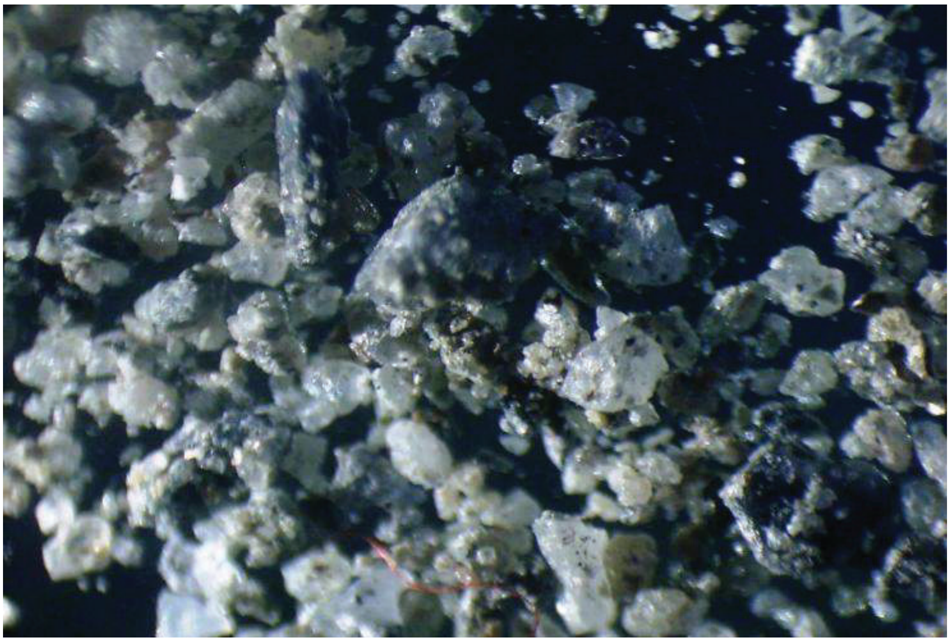
The design feed rate to the plant is 150 t/h and this produces 80 t/h of glass grade sand with an additional 50 t/h of concrete sand. The plant accepts -120 mm feed to the M4500 hopper and this material is then transferred to the integrated ProGrade double deck rinsing screen. The top deck removes the 40-120 mm material to a stockpile while the bottom deck sends the 7-40 mm material to another stockpile. The 0-7 mm material collects in the ProGrade sump and is then pumped to a five deck fines screen. At this point the silica sand is screened at 0.43 mm and the 0.43 mm to 7 mm material is sent to a separate EvoWash sand washing plant to allow for the production of concrete sand. Meanwhile, the 0-0.43 mm material is sent to an EvoWash fines recovery plant where following delivery to the EvoWash sump the material is then pumped to the integrated hydro-cyclone which removes the -63 μm material. The cyclone overflow containing the waste material is then sent to the AquaCycle thickener.

The underflow from the cyclone is delivered to the EvoWash dewatering screen before being transferred to the attrition cells. The function of the attrition cells is to assist with the removal of iron oxide and other deleterious materials from the silica sand. The iron oxide is adhered to the silica particles and must be scrubbed from the surface of the particles to allow removal later in the process. Refractory heavy minerals and iron oxide particles are then separated from the silica sand through the introduction of spiral classifiers. As these particles have a higher specific gravity than the silica sand particles, the spirals are able to perform the required separation. The rejects from the spirals – a sand product containing the liberated heavy mineral and iron oxide – is delivered to the EvoWash sand washing plant sump and is destined for the concrete sand product. The silica sand slurry is delivered to the sand sump on the M4500 where it is then pumped to the integrated counter flow classification unit (CFCU).

The CFCU unit is used to remove the <106 μm particles from the sand or as required by the customer specifications. The CFCU is an upward flow classifying unit which operates on the principle that an upward flow of water will cause the lighter particles to rise and the heavier particles to sink. This facilitates the removal of any remaining fines while the silica sand slurry is then delivered to a dewatering screen. The dewatered silica sand is transferred via an integrated stockpile conveyor. The fine material removed in the CFCU is sent to the concrete sand Evowash for recovery into the concrete product.

From an initial iron oxide (Fe_2O_3) content in the feed of 3% the glass grade sand is required to achieve 0.25% Fe_2O_3 or in line with customer sand specification for colored glass. The final product has less than 0.1% iron oxide. The Fe_2O_3 content in the final silica sand product is reduced to 0.1% ensuring that it meets the requirements of solar grade sand customer specifications. Both the dewatered silica sand and concrete sands are subsequently stockpiled using 36 m radial conveyors which ensure a stockpile capacity of 20,000 t. From an initial silica content of 80-85% for the excavated material the final product achieves +99% silica. Waste water from the plant is processed by the AquaCycle thickener which recovers 90% of the water for re-circulation around the washing plant. The plant requires 900 m^3 per hour of water for its operation and the introduction of the AquaCycle ensures that the top up water supply is only 90 m^3 per hour. The sludge from the AquaCycle thickener is pumped to on-site settling ponds and then transported back as landfill materials.

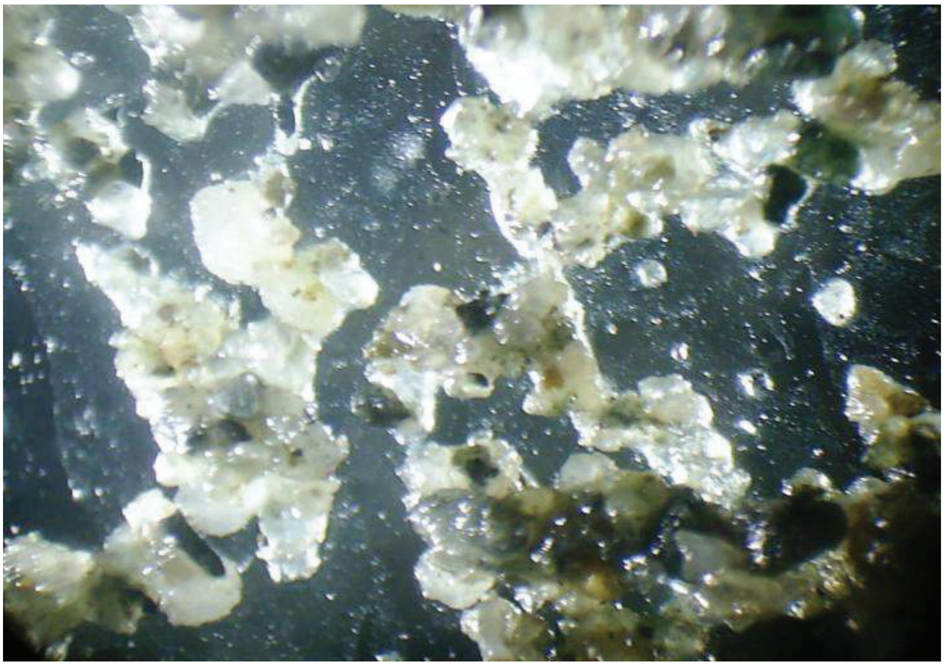
The Neaua Silica Sand Deposit contains a very large amount of small, sub-rounded , sub-angular and angular sand (approx. 80 - 85%) with a very small suspended matter content (*Figure 22*). The sand layers lie horizontally, in great thicknesses and alternate with fine clay layers, between 360 and 540 m above sea level.



22. fig. - Neaua unprocessed sand grains (x10)

With a special processing technique in a CDE equipment as described, a large amount of calcite ($CaCO_3$) and deleterious impurities are removed with the washing water, and the quartz content of the sand fluctuates between 94-96% (*Figure 23*). In this state, the quartzous sand is a good raw material for concrete and dry plasters production, for the tiles adhesives industry and other construction materials production processes.

.

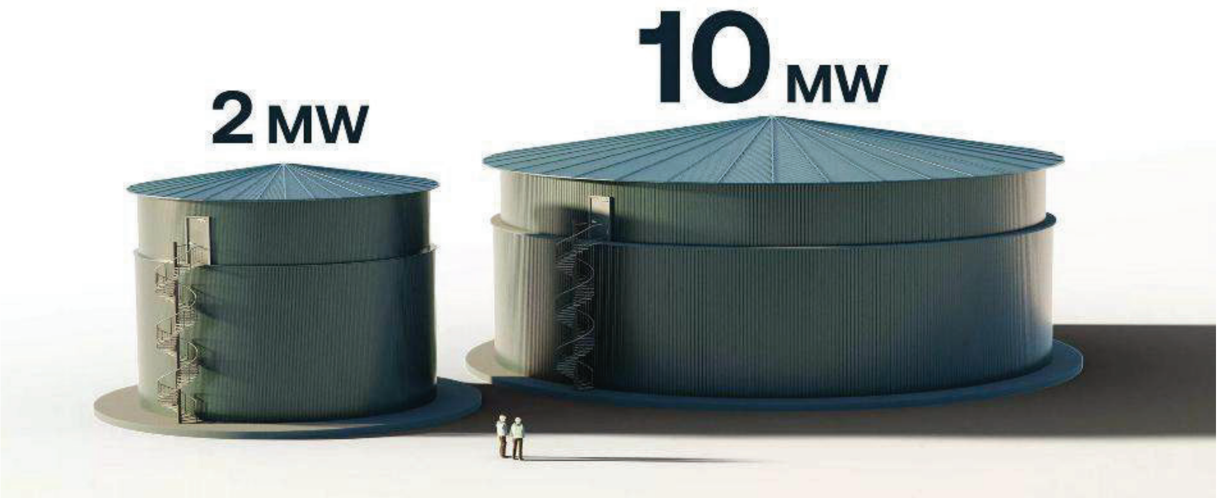


23. fig. – Neaua one-time washed sand grains (x10)

After the second washing session and subsequent processing using the attrition technique—or alternatively, a single processing cycle in a 0.1% concentration HCl acid formula—residual calcite ($CaCO_3$) and other impurities are effectively removed. The resulting "enriched" high-grade quartz/silica sand achieves a quality level highly suitable for advanced applications, including the production of high-end products such as solar panels, glass, abrasives, and even semiconductors (Figure 24). Furthermore, by incorporating an additional gravity and electromagnetic separation module, leached calcite and heavy minerals can be efficiently recovered and marketed as valuable secondary by-products.

24. fig. - Neaua two-times washed sand grains

In this state, besides the application range described above, the obtained silica sand could also be used to establish so called sand batteries to store solar energy to be used later on. This works by a process called resistive heating, whereby heat is generated through the friction created when an electrical current passes through any material that is not a super conductor. The hot air is then circulated in the container through a heat exchanger. The sand can store heat at around 500^{C} for several months, providing a valuable store of cheaper energy during the winter. When needed, the battery discharges the hot air - warming water in the heating network. Homes can all benefit from this technology.



Products

Sand Battery 2 MW

Affordable and sustainable heat production

A compact solution to make your heat production more affordable and sustainable. Ideal for small-to-mid-sized industrial facilities, space heating, or district heating networks.

- Mid-sized high-temperature thermal energy storage system
- 2 MW heating power with a capacity of 200 MWh
- Scalable to meet higher heating demands
- Approximate round trip efficiency 85%
- Approximate dimensions: 15 x 12 m
- Reduces reliance on fossil fuels, cutting emissions and operational costs
- Easily integrates into existing energy systems

Sand Battery 10 MW

Make an entire energy system climate-neutral

Designed to decarbonize entire energy systems, perfect for large-scale industrial processes, energy companies, district heating networks, or space heating needs.

- Large high-temperature thermal energy storage system
- 10 MW heating power with a capacity of 1000 MWh
- Scalable to meet even greater heating demands
- Approximate round trip efficiency 90%
- Approximate dimensions: 30 x 12 m
- Dramatically reduces carbon emissions and energy costs
- Modular and flexible for easy integration with renewable energy sources

Applications

Water

Provide hot water for district heating and other heating systems, reduce energy costs and carbon emissions.

Air

Deliver hot air for space heating, drying, calcination, and other industrial processes, improve efficiency and sustainability.

Steam

Generate hot steam for industrial processes like manufacturing and power generation, offering a clean alternative to fossil fuel-based systems.

Electricity*

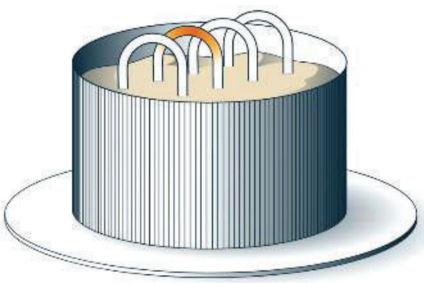
A future Power-to-Heat-to-Power (P2H2P) product will convert stored energy back into electricity. *Expected to be ready by 2026.

How Does it Work?

A solution to mitigate climate change

The world is increasingly turning to renewable energy to combat climate change and reduce pollution. However, intermittent sources like solar and wind only produce energy when the sun shines or the wind blows, creating a mismatch between energy production and consumption.

As the share of renewables grows, energy storage becomes critical for maintaining grid stability and storing energy for later use. The Sand Battery efficiently stores large amounts of intermittent energy for extended periods and returns it as highly valuable heat when needed.



Storing renewable energy

The system charges by using electricity from the grid or local renewable sources such as solar PV or wind farms, storing energy when clean and low-cost electricity is available. Energy is transferred to the Sand Battery through a closed-loop heat transfer system. When heat is needed, it's discharged via a heat exchanger.

Hot Water | **Process Steam** | **Hot Air**

The Sand Battery can deliver hot water, steam, or air, with output temperatures of up to 400°C. We are also developing a solution to convert stored heat back into electricity. This heat is suitable for example water-based heating networks or for generating process steam in industrial applications.

Around 36% of all industrial process heat falls within the temperature range of Polar Night Energy's Sand Battery. These processes, currently dependent on oil and gas, can now be decarbonized through our non-combustion technology.

Silicon ingot production is a critical process in the manufacturing of semiconductors and photovoltaic (PV) solar cells. The process typically involves pulling monocrystalline or multi-crystalline silicon ingots from highly purified molten silicon. These ingots are subsequently sliced into thin wafers that serve as the foundation for a wide range of electronic and solar products.

From Quartz to High-Purity Silicon: The Origin and Occurrence of Silicon - Silicon is synthesized within the interiors of massive stars, where temperatures exceed 10^9 K, through the fusion of oxygen nuclei. At the culmination of these stars' lifetimes, during supernova explosions, silicon and other elements are ejected into the universe. While hydrogen and helium dominate the visible matter of the universe, silicon constitutes less than 0.1% of the total cosmic mass.

In our solar system, which formed from the remnants of earlier stellar explosions, silicon has become enriched, particularly within the inner planets. These planets, being closer to the sun, have lost much of their volatile elements. On Earth, silicon accounts for approximately 17% of the planet's total mass, making it the third most abundant element after oxygen and iron, closely followed by magnesium.

Within the Earth's iron-dominated core, silicon is the second most abundant element, comprising roughly 7% of its mass. In the Earth's crust, which spans approximately 40 km in thickness, silicon is present at concentrations of about 28%, primarily in the form of silicate minerals, quartz (SiO_2), and silica ($Si(OH)_4$). In the oceans, silicon exists as dissolved silica, making it the second most common element after oxygen. However, the occurrence of pure elemental silicon in nature is negligible in terms of volume.

Production and Use of Metallurgical-Grade Silicon - For the production of elemental silicon, quartz sand (SiO2) is reduced in smelting reduction kilns (*Fig. 2*) at approx. 2000°C with carbon to metallurgical-grade silicon (MeG-Si) with a purity of about 98 - 99%.

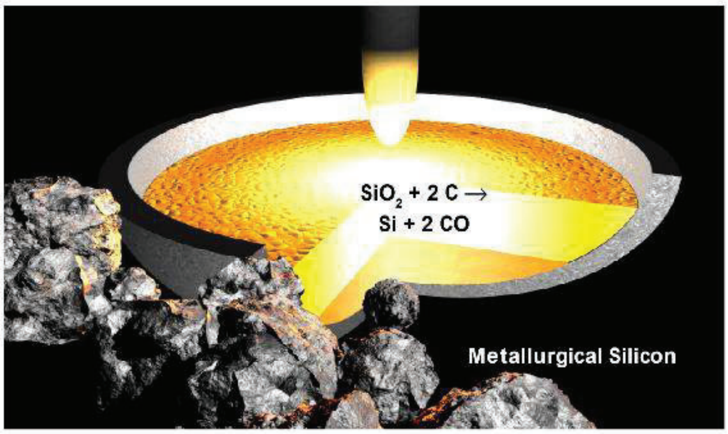


Fig. 2: Quartz sand (above) is reduced with graphite in smelting reduction furnace (schematically, right) to raw silicon.

The Metallurgical-Grade Silicon is produced out of quartzite SiO_2, which consists to 46% out of Silicon (Si), to 53% out of bimolecular Oxygen (O2) and impurities. Silicon is obtained commercially by heating sand, charcoal and coke in an electric furnace. Charcoal is required to reduce the silica to silicon (ie. $SiO_2 + 2C = Si + 2CO$) – a process that is sensitive to its quality. The carbon also acts as a conductor in the electric arc furnace and a reaction bed. At about 1650°C the chemical reaction starts: the SiO_2 is giving away one oxygen atom. In this case, the chemical combination SiO is generated at greater lots. On the one hand, the gaseous SiO reacts under the creation of CO which results during "combustion" of the carbon by formation to raw silicon or metallurgical grade silicon in the melt. On the other hand, the gaseous SiO reacts with oxygen contained in the stove air in exhaust again to SiO_2, however in finest beads. These beads are reprocessed technically for use as micro-silica and are used as a temperature constant filling material e.g. in ceramic and fireproof products. The liquefied silicon melt is collected in the bottom of the furnace, and is then drained and cooled. The silicon produced via this process is called metallurgical grade silicon and is at least 99% pure. With pure raw materials and electrodes, the degree of purity is also significantly higher. The majority of the world production which is done mainly in China and Russia (in 2022 about 17 million tons) is used as an alloy component for steel and aluminum, as well as a raw material for the production of silicones. Only about 12% of the raw silicon is prepared for hyper-pure silicon as described in the following section, of which approximately 90% is used for the manufacture of silicon solar cells. Some 150k tons a year are ultimately used in the production of silicon wafers for the semiconductor sector, which this chapter is devoted to.

Preparation of Metallurgical-Grade Silicon to Hyper-pure Silicon - The concentration of impurities in the raw silicon is too high by many orders of magnitude for use as a semiconductor in the microelectronics or photovoltaics. To achieve the required electronic properties, the metallurgical-grade silicon must be “refined” to hyper-pure silicon. In the first step to ultra-pure silicon, metallurgical-grade silicon is converted into trichlorosilane ($HSiCl_3$) via $Si + 3\,HCl \rightarrow HSiCl_3 + H_2$ at about 300°C with HCl where many impurities such as iron, which does not form volatile chlorine compounds at these temperatures, is removed. Trichlorosilane mixed with other gaseous chlorine compounds undergoes multiple distillations thereby improving the purity up to 99.9999999 % (“9N”) and is subsequently thermally decomposed to poly-crystalline silicon. The poly-crystalline silicon formation is performed in the so-called Siemens process where the purified trichlorosilane mixed in hydrogen is thermally decomposed on the surface of a heated (approx. 1100°C) silicon rod via $HSiCl_3 + H_2 \rightarrow Si + 3\,HCl$ to poly-crystalline silicon and HCl which corresponds to the reverse reaction of the trichlorosilane formation.

About 80% of the world's polysilicon is produced using the Siemen's process developed in the 1950s. (a) Basic Siemen's reactor. (b) As grown polysilicon rods after a reactor run. (Current generation reactors have many more rods.) (c) Final polysilicon chunks ready for loading into a crystal growth furnace.

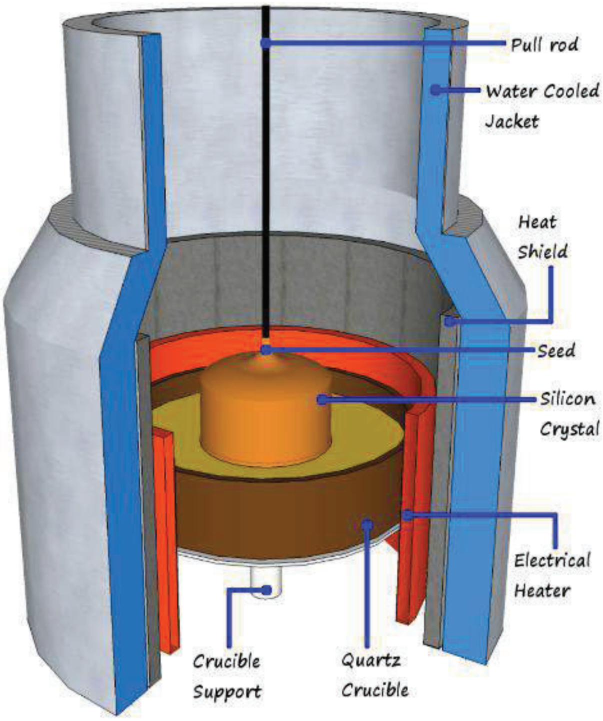
Poly-crystalline and Mono-crystalline Silicon - The poly-crystalline silicon attained in the Siemens process has, compared with electronic-grade material (purity concentration $<10^{14}$ cm^{-3}), a high degree of purity but crystalline grain boundaries which form electronic defects reducing the efficiency of solar cells produced with it and excluding its use in the field of microelectronics. As the basic raw material for the production of silicon wafers as substrates for microelectronic components, only mono-crystalline silicon which is produced from poly-crystalline silicon using the Czochralski or Float-zone methods as described in the following sections comes into question. In this case, specific and well-defined doping of the silicon with foreign atoms is also done in order to define the electrical conductivity of the wafers produced with it and to adjust it homogeneously over the entire crystal.

(Historical significance - Monocrystalline silicon (mono-Si) grown by the Czochralski process is often referred to as monocrystalline Czochralski silicon (Cz-Si). It is the basic material in the production of integrated circuits used in all types of modern electronic equipment and semiconductor devices, e.g., computers, TVs, mobile phones etc. Monocrystalline silicon is also used in large quantities by the photovoltaic industry for the production of conventional mono-Si solar cells. The almost perfect crystal structure yields the highest light-to-electricity conversion efficiency for silicon. The method of mono-crystalline silicon growth for large scale industry application started some 30 year later after the method was invented. A year before leaving AEG company in Berlin, in 1916, J.Czochralski wrote a paper on the crystal growth method, later named the "Czochralski method". The paper was received by the editorial board on August 19, 1916 and was published in 1918, with a two year delay [J. Czochralski, "Ein neues Verfahren zur Messung des Kristallisationsgeschwindigkeit der Metalle", Z.Phys. Chem. 92, 219 (1918)]. In the scientific literature, the year 1916 was adopted as the date of elaboration of the method. The idea of Czochralski method is based on pulling a crystal from the melt against gravity forces. This feature constitutes an important difference in respect to other known crystal growth methods. Czochralski has grown single crystals of tin, zinc and lead by this simple method and investigated their rate of crystallization. The paper provided a description of a device, which contained a silk thread with a holder and was completed with a glass rod. A part of the glass immersed in the molten metal was covered with a metal layer, and then the growth was continued. The obtained wires were of about 1 mm diameter and had up to 150 cm in length. The Czochralski method was improved and cited by some authors from the very beginning. For example, in 1918 Wartenberg used a seed zinc wire to grow the crystals of zinc. Later, in 1922, Gompez called this method for the first time the Czochralski method. Later, works describing the method were written by Mark et al. in 1923, by Sachs in 1925 and by others. After invention of germanium-based transistor in 1947, Gordon K. Teal from Bell Laboratory used the Czochralski method to obtain germanium single crystals. The first single crystal of germanium was obtained in 1948 and the results were presented at the Oak Ridge Meeting of the American Physical Society in 1950, and were reported in G.K. Teal, Phys. Rev. 78, 647 (1950). One of the sentences confirms the used method: "germanium single crystals of a variety of shapes, sizes and electrical properties have been produced by means of a pulling technique distinguished from that of Czochralski and others in improvement". It should be noted that the Czochralski method of crystal growth is continuously improved and developed with regard to the technical level of process automation and including thermodynamic considerations of growth processes even today. It permits to prepare a high quality bulk single crystals, among them silicon, as well as a multitude of oxides, fluorides, metals and alloys, multi-component compounds and solid solutions. Now, the main advantages of the Czochralski method are growing single crystals in defined crystallographic orientations with different sizes, shapes, which are mainly limited by a design of crystal puller.)

Introduction - The Czochralski (Cz) process is a well established method for growing large scale single crystals of semiconductors, metals, salts and gemstones. A single crystal (mono-crystalline) is a material in which the crystal structure is near perfect, i.e., the arrangement of the atoms or molecules exhibit strict order. The most important use of the method is the growth of semiconductors, particularly that of mono-crystalline silicon, which cannot easily or inexpensively be grown using other methods. Silicon is a particularly important material because it has many desirable properties; it is abundant and cheap, strong and its semiconducting properties are excellent. Today, solar cells made from crystalline silicon (Si) substrates have a share in excess of 90% of the global solar cell market, and they are likely to continue to dominate this market in many years to come. The efficiency of a solar cell is to a large extent dependent on the structure of the wafer, which, in turn depends on the crystallization of the grown crystal (ingot). The solidification process is therefore an important step in reducing PV energy costs and increasing cell efficiency.

In the Cz process, the solid silicon is placed in a crucible. Electrical heaters are used both to melt the silicon, and to maintain an appropriate temperature trajectory throughout the crystallization process. A single crystal seed is put in contact with the molten silicon. The seed is then slowly withdrawn from the melt, and surface tension causes the formation of a meniscus which connects the crystal to the melt. As the crystal is withdrawn, the melt solidifies along the top of the meniscus, causing the crystal to grow. The surface along which the material solidifies is referred to as the (crystal-melt) interface. In order to grow a crystal with acceptable shape and quality, the heater power as well as the pulling speed are manipulated appropriately during the growth process. After a brief period producing a thin crystal (to allow dislocations caused by the thermal shock when the seed crystal is dipped into the melt to propagate out of the crystal), the crystal diameter is increased quite quickly, whereas for most of the duration of the process it is desirable to keep the crystal diameter constant. In the case of solar cell production, the ingot is sliced into very thin wafers when the crystallization process is over. Each wafer is polished and cut into a specific shape, depending on the final application. A sketch of the Czochralski process is shown in the following figures. During growth, the radius (diameter) of the crystal is typically measured by a CCD camera aimed at the meniscus, which can be identified as a 'glowing ring' due to reflections from the glowing hot environment. Since the CCD camera is calibrated to be aimed at the meniscus, the melt level must be the same at all time. The other measurements required in this simulation study are two temperatures from the hot-zone of a Czochralski furnace. Pulling speed and heater power are the two major actuator inputs for the Cz crystal growth process, but they influence the material solidification process at the interface in different ways. The heater power affects the energy balance at the interface region, while the pulling rate acts on the crystal radius through manipulation of meniscus shape and growth angle. To keep the growth process operating uniformly in terms of constant crystal radius and growth rate, the pulling speed should match the growth rate for the applied heater power. Growth rate and crystal shape are such alternative control objectives which have an impact on the crystal quality, as these are tightly coupled with crystal heat fluxes and melt conditions.

The Czochralski process is a typical batch process where the operating conditions are time varying and where steady state is never reached. This mainly results from the fact that the whole system configuration changes during the growth, and in particular, the falling melt level leads to an ever-changing heat entry from the heaters into the system. Furthermore, the process is highly complex and requires careful control throughout the whole crystal production.



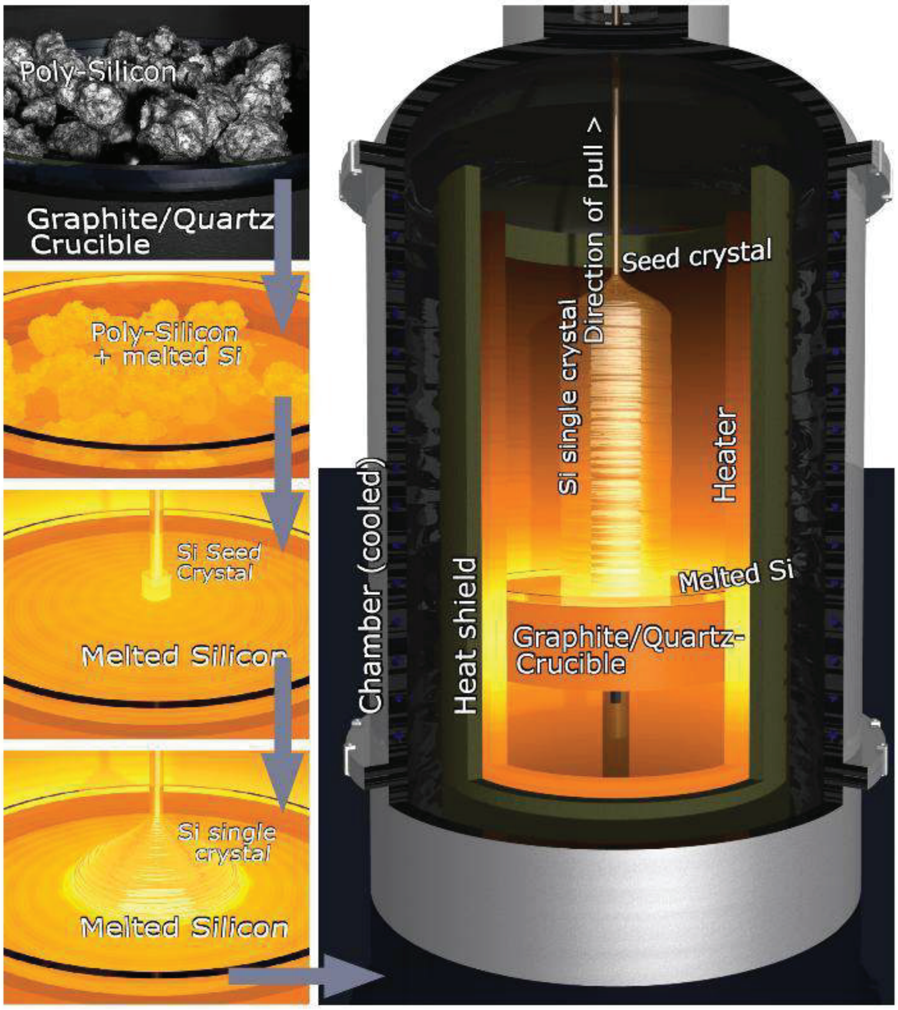


Fig. 4: A diagram of the Czochralski technique:

Top left: A quartz crucible filled with poly-crystalline silicon fragments from the Siemens process

Left 2nd from above: The silicon fragments are melted together with doping material

Left 3rd from above: A mono-crystalline seed crystal is dipped into the molten silicon

Bottom left: The seed crystal pulls a doped single crystal from the melt

Large image on the left: The schematic structure of a chamber for the crystal growing process in the Czochralski technique

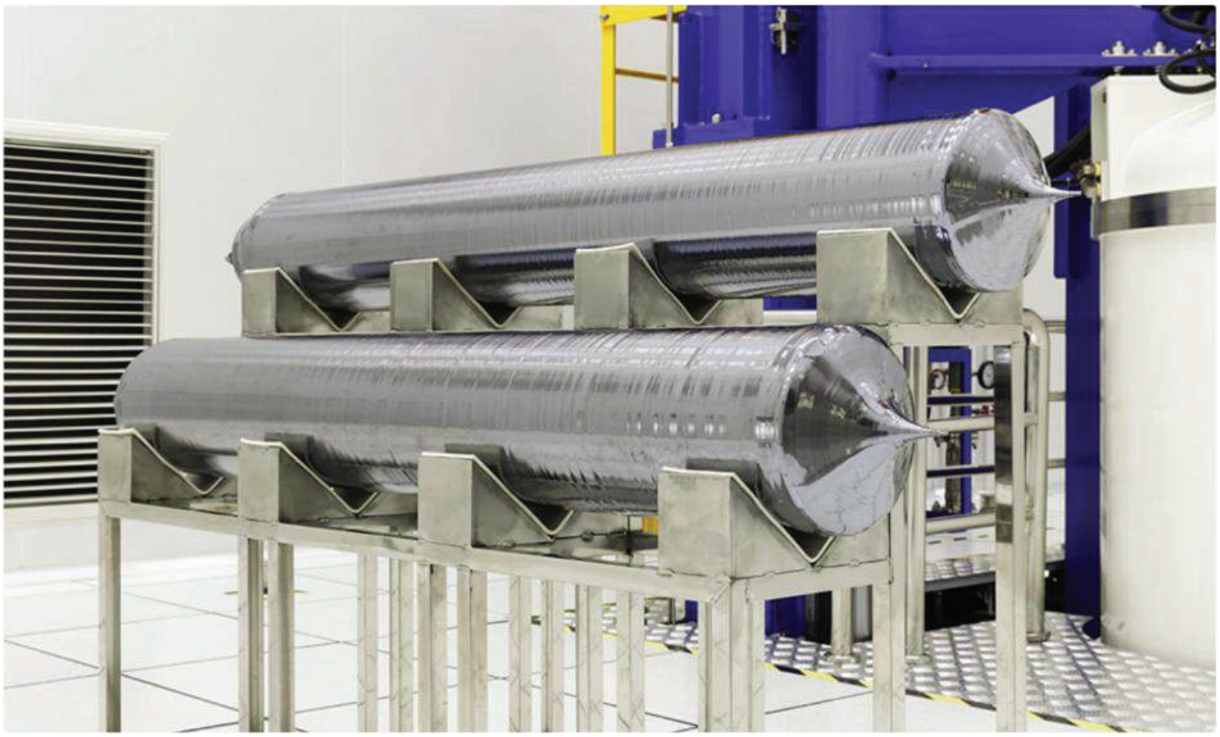
Czochralski growth, also known as ***crystal pulling***, works by utilising the concept of heterogeneous nucleation to initiate the solidification of a molten material onto a seed crystal, ultimately resulting in the formation of a larger, high-quality single crystal. The following is a brief breakdown of the process phases:

- ***Melt Preparation***: The desired material (for instance, silicon) is placed in a high-purity quartz crucible and heated above its melting point using induction or resistance heating. The quartz crucible is chosen due to its superior thermal stability and minimal chemical reactivity with the melt at high temperatures.
- ***Seed Crystal Introduction***: A high-purity, single-crystal seed with a defined crystallographic orientation is dipped into the molten material. This seed serves as a substrate for the growth of the new crystal, dictating its crystallographic structure.
- ***Pulling & Rotation***: The seed crystal is subjected to a controlled vertical pulling while being simultaneously rotated around its axis using a growth chamber rotation mechanism. This creates a well-defined molten zone around the seed-melt interface.
- ***Crystallization***: As the seed is pulled upwards, the molten material near the seed-melt interface experiences a decrease in temperature, triggering crystal nucleation. The crystal growth then proceeds via a layer-by-layer deposition of atoms onto the seed crystal, following the same crystallographic orientation as the seed due to the templating effect.
- ***Temperature Gradient Control***: A precisely controlled temperature gradient is essential throughout the growth process. The melt temperature (Tm) needs to be maintained slightly above the liquidus (temperature above which a material is completely liquid, Tl) to ensure sufficient melt availability for crystal growth. However, an excessively high Tm can lead to unwanted phenomena such as evaporation or decomposition of the material. Conversely, a temperature profile that is not sufficiently above Tl can hinder crystal growth or cause the formation of polycrystalline defects.
- ***Rotational Control***: The implementation of a controlled seed rotation (ω) plays a critical role in maintaining a uniform melt distribution around the seed-melt interface. This mitigates the development of thermal and compositional striations within the growing crystal, ultimately enhancing crystal quality.
- ***Solidification***: By meticulously regulating the pulling rate (vpull), rotation rate (ω), and temperature gradient (dT/dz), a large, high-quality single crystal can be progressively solidified from the melt. The solidification process is carefully monitored to ensure a defect-free crystal with the desired diameter and electrical properties.
- ***Inert Atmosphere***: The entire Czochralski growth process is typically conducted within a precisely controlled inert atmosphere, such as high-purity argon. This prevents contamination of the melt and the growing crystal by reactive gases like oxygen or nitrogen, which can significantly deteriorate crystal quality.

A key technology in this production process is the silicon ingot puller, used in the Czochralski (CZ) process, which is the predominant method for producing high-quality single-crystal silicon ingots for semiconductors and solar applications.

The ***silicon ingot puller*** is the primary piece of equipment that facilitates the Czochralski process. It ensures precise control over temperature, pulling speed, and rotational movement—three critical factors in achieving high-quality single-crystal ingots. The performance of the puller directly affects the quality of the silicon wafers and, consequently, the performance of the end products (semiconductors or solar cells).

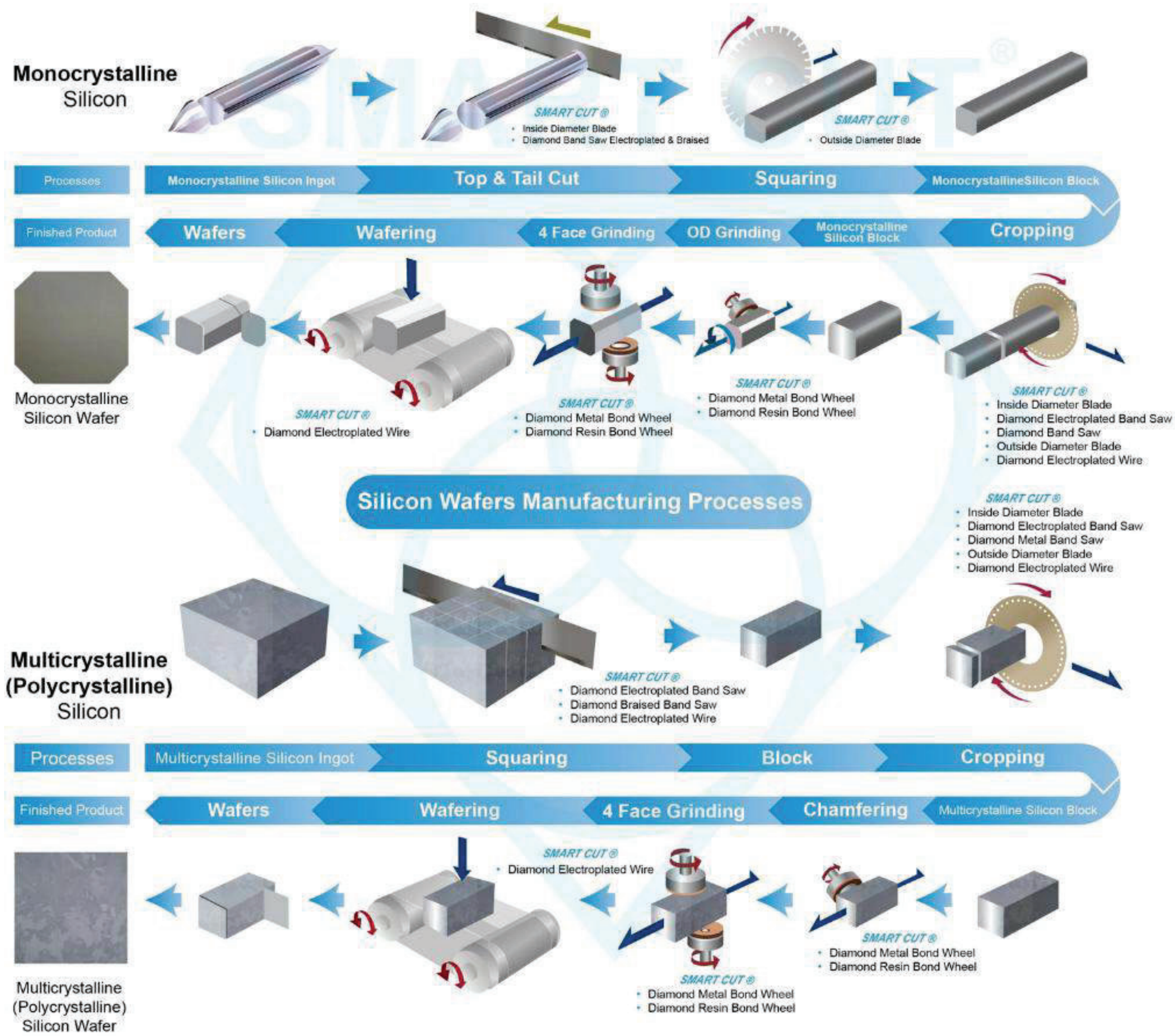
Monocrystalline silicon ingots produced through the Czochralski process are primarily used in the semiconductor industry. These ingots are sliced into wafers that serve as the base material for integrated circuits, transistors, and other semiconductor devices. The ultra-high purity of the silicon and the defect-free crystal structure are essential for high-performance electronics.



In the photovoltaic (PV) industry, both monocrystalline and multicrystalline silicon ingots are used to manufacture solar cells. Monocrystalline silicon, produced using the CZ process, has the highest efficiency in converting sunlight into electricity, making it the preferred choice for high-performance solar panels.

Improving the yield of defect-free silicon ingots is a constant challenge. Advanced control systems, better materials for crucibles, and improved cooling techniques are being researched to further enhance ingot quality and yield. The ability to produce defect-free, single-crystal silicon ingots ensures that the silicon wafers derived from them are of the highest quality. The production of silicon ingots using silicon ingot pullers is a complex and precise process that plays a pivotal role in both the semiconductor and solar industries. Through the use of advanced technology, strict quality control, and continuous innovation, the process has become a cornerstone in meeting the global demand for high-purity silicon in the electronics and renewable energy sectors.

The production of Monocrystalline Silicon Wafers, an essential component in semiconductor manufacturing, involves several intricate steps to ensure precision and quality. The journey begins with the formation of the monocrystalline silicon ingot (described and shown above), typically produced using the Czochralski (CZ) method.



The operational phases of wafers production are the following:

- **Cutting for Top and Tail -** The next step is to cut the top and tail of the ingot. This step ensures that any impurities or defects that may have accumulated at the ends during the crystal growth are removed, providing a uniform starting material for subsequent processes.
- **Squaring -** Once the top and tail are cut, the ingot undergoes a squaring process. Here, the cylindrical ingot is shaped into a square or rectangular cross-section. This transformation facilitates easier handling and further processing, optimizing the ingot for the wafering process.
- **Silicon Block Formation -** After squaring, the silicon is cut into blocks. These silicon blocks are more manageable units that can be precisely processed into wafers.
- **Cropping -** The silicon blocks then go through cropping, where they are cut into smaller, more uniform pieces. This step is crucial for ensuring consistency in the size and shape of the wafers produced.
- **Outer Diameter (OD) Grinding -** To achieve the required thickness and surface finish, the wafers undergo OD grinding. This process ensures that the wafers are uniformly thin and smooth, which is essential for subsequent semiconductor device fabrication.
- **Chamfering -** Chamfering the edges of the wafers is done to prevent chipping and breakage during handling and processing. This step involves beveling the edges to create a more durable and resilient wafer.
- **Face Grinding Wafering -** Wafering involves slicing the cropped silicon blocks into thin wafers using diamond wire saws or other precision cutting tools. This step is critical, as the thickness and flatness of the wafers must be controlled meticulously to meet industry standards.
- **Final Product: Monocrystalline Silicon Wafer -** The final product of this series of processes is the monocrystalline silicon wafer, ready for further processing in semiconductor manufacturing.

The cutting of the top and tail of the silicon ingot is a critical process in the production of high-quality silicon wafers. This step, often overlooked in its complexity, plays a vital role in ensuring the integrity and uniformity of the final product. Let's delve deeper into why this step is necessary, the techniques used, and its impact on subsequent processes.

Impurity Removal - During the crystal growth process, impurities tend to accumulate at the ends of the silicon ingot. These impurities can originate from several sources, including the initial raw materials, the crucible used in the growth process, and the environment in which the ingot is grown. By cutting off the top and tail of the ingot, manufacturers can remove these impurity-laden sections, thereby ensuring that the remaining ingot is of the highest purity.

Defect Elimination - Defects such as dislocations, grain boundaries, and other crystallographic imperfections are often more prevalent at the extremities of the ingot. These defects can compromise the mechanical strength and electronic properties of the wafers. By eliminating the top and tail sections, manufacturers can minimize the presence of these defects in the final product, leading to wafers with better performance characteristics.

Uniform Starting Material - The removal of the top and tail also helps in achieving a uniform starting material for subsequent processes. This uniformity is crucial for maintaining consistency in the wafering process, which directly impacts the quality and yield of the final wafers. A uniform ingot ensures that the wafers sliced from it will have consistent properties, which is essential for high-precision applications in the semiconductor industry.

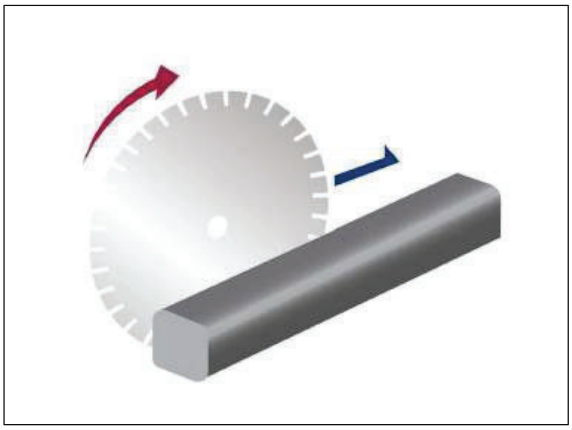
Inside Diameter Diamond Blades - One of the most common tools used for cutting the top and tail of silicon ingots is the diamond blade. Diamond blades are renowned for their hardness and precision, making them ideal for cutting through the tough, crystalline structure of silicon. These blades can be configured to cut at various depths and speeds, ensuring a clean and precise cut that minimizes damage to the ingot.

Diamond Wire Saws - Wire saws are another popular method for cutting silicon ingots. These saws use a thin wire embedded with diamond abrasives to slice through the silicon. The wire saw method is particularly advantageous for its ability to produce very thin cuts with minimal kerf loss (the amount of material removed during the cutting process). This precision helps in maximizing the usable material from each ingot.

Diamond Band Saw Blades - One of the key advantages of using diamond band saw blades for silicon cutting is their ability to provide high precision cuts. This is crucial for applications where accuracy is critical, such as in the semiconductor and photovoltaic industries. Additionally, diamond blades minimize chipping and cracking, thereby maintaining the integrity of the material. They also produce a smooth surface finish, which reduces the need for extensive post-processing. Furthermore, diamond band saw blades have a longer lifespan compared to conventional blades when cutting hard and brittle materials like silicon.

CUTTING METHOD	PRECISION	CHIPPING/ CRACKING	SURFACE FINISH	BLADE LIFE	CUTTING SPEED	COOLING REQUIREMENT	MAINTENANCE	BEST APPLICATIONS
Diamond Band Saw Blade	High	Minimal	Smooth	Long	Moderate	High	Regular blade and equipment maintenance	Semiconductor, photovoltaic industries
Diamond Wire Saw	Very High	Very Minimal	Very Smooth	Long	Slow to Moderate	High	Frequent wire inspection and replacement	Advanced ceramics, semiconductor wafer slicing
Laser Cutting	High	Minimal to Moderate	Very Smooth	N/A	Fast	Moderate (air cooling)	Regular calibration and maintenance of laser	Precision machining, intricate patterns
Outside Diameter Diamond Blades	Moderate	Moderate to High	Moderate	Short	Fast	Low	Frequent blade replacement	General rough cutting, lower precision applications
Waterjet Cutting	Moderate to High	Minimal	Smooth	N/A	Moderate to Fast	Very High (water and abrasive)	Regular nozzle and pump maintenance	Complex shapes, versatile materials
ID Diamond Cutting Blade	Very High	Very Minimal	Very Smooth	Long	Slow to Moderate	High	Regular inspection and dressing of the blade	Semiconductor wafer slicing, high-precision applications

Squaring is a crucial step in the preparation of ingots for the wafering process, particularly in industries dealing with semiconductors, solar cells, and various advanced materials. After the top and tail of the ingot are removed—a process that eliminates irregularities and potential contaminants—the ingot is transformed from its original cylindrical shape into a square or rectangular cross-section. This section delves deeper into the significance, methods, and considerations involved in the squaring process.



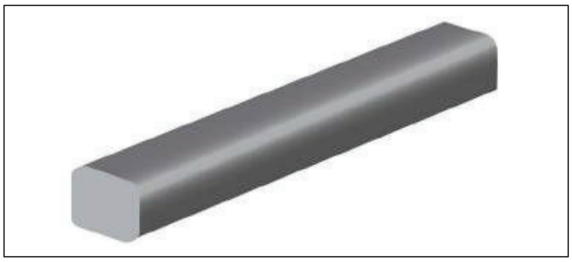
The primary purpose of squaring is to prepare the ingot for efficient and precise slicing in the subsequent wafering stages. A square or rectangular cross-section provides several advantages:

- *Uniformity and Consistency:* Squared ingots ensure that wafers are produced with consistent dimensions and properties, which is critical for the high standards required in semiconductor manufacturing and photovoltaic applications.
- *Optimal Use of Material:* By converting the cylindrical ingot into a squared shape, manufacturers can maximize the use of the material, reducing waste and improving the yield of valuable wafers.
- *Enhanced Handling and Mounting:* Squared ingots are easier to handle, align, and mount on slicing equipment, which reduces the risk of errors during the cutting process.

Several techniques can be employed for squaring ingots, each utilizing distinct tools and technologies. Band sawing involves using a band saw equipped with diamond-impregnated blades to shape the ingot. This method is particularly favored for its ability to handle large ingots and its relatively low operational cost. Wire sawing is preferred for materials that require a high level of precision and minimal material loss. This technique employs a wire coated with abrasive particles to slice through the ingot, delivering high accuracy and smooth surfaces. An advancement of traditional wire sawing, multi-wire sawing, uses multiple wires simultaneously, significantly increasing both the throughput and efficiency of the squaring process.

When squaring ingots, it's crucial to manage several factors carefully to ensure optimal results. The choice of blade, whether for band sawing or wire sawing, is critical. Factors such as the blade’s material, grit size, and concentration must be matched to the ingot’s composition and the desired cut quality. Parameters like cutting speed, feed rate, and coolant flow must be optimized to minimize defects such as chipping and thermal damage, which can adversely affect the wafer's quality. Proper handling and precise alignment of the ingot before squaring are essential to avoid misalignments that can lead to material wastage and non-uniform wafers.

Silicon block formation is a crucial intermediate step in semiconductor manufacturing, occurring right after the squaring of the silicon ingot. This phase involves cutting the squared ingot into smaller, more manageable units known as silicon blocks. These blocks serve as the



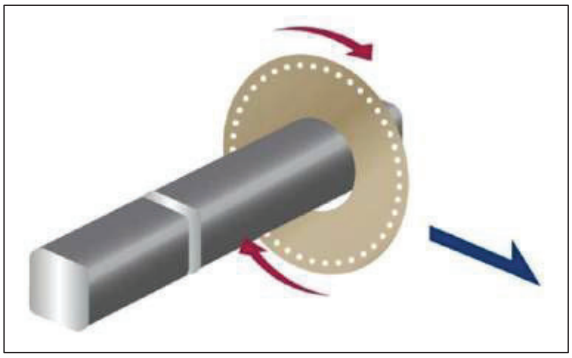
precursors to silicon wafers, which are essential components in the production of semiconductor devices.

Once the ingot has been squared, ensuring uniformity and structural integrity, it undergoes the block formation stage. Here, the large squared ingot is segmented into blocks using highly precise and controlled cutting techniques. Precision wire sawing, which employs a wire saw that operates with a thin, diamond-coated wire, is favored for its ability to make clean, precise cuts with minimal material loss. For larger ingots, ID sawing (Internal Diameter Sawing) is often used. This technique utilizes a large circular blade to slice through the silicon, maintaining consistent thickness throughout the block.

The transformation of squared ingots into smaller blocks enhances manageability. By reducing the size of the silicon from large ingots to smaller blocks, manufacturers can handle and process the material more efficiently. Smaller blocks are easier to manipulate, inspect, and transport, facilitating smoother operations throughout the manufacturing process. Additionally, smaller blocks allow for more precise control during the wafering process, crucial for ensuring that the wafers are uniform and meet the strict thickness and flatness specifications required for high-quality semiconductor devices.

However, despite its advantages, silicon block formation presents certain challenges. Maintaining the dimensional accuracy of each block is critical; any deviation in size can lead to significant issues during the wafering phase, affecting the uniformity and quality of the final wafers. The cutting process must also be meticulously controlled to avoid introducing defects such as cracks or impurities into the silicon, as these defects can propagate during subsequent processing stages, compromising the quality of the wafers. Additionally, each cut into the silicon ingot potentially results in material loss. Optimizing the cutting process to minimize waste is crucial, especially given the high cost of pure silicon.

After silicon blocks are formed, they proceed to the ***cropping*** stage, where they are cut into smaller, more uniform pieces. This step is crucial in the wafer production process, as it ensures consistency in the size and shape of the wafers that are eventually produced. Cropping is typically done using precision cutting tools that can accurately measure and slice the silicon blocks to required specifications.

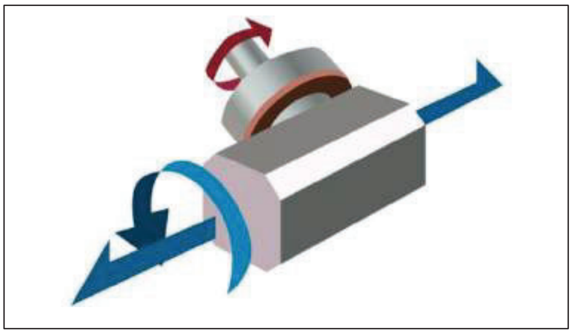


The main goal of cropping is to refine the block dimensions further, making them perfectly suited for the next stages of wafer processing. This involves cutting the blocks into precisely measured, smaller sections, which facilitates better handling and more efficient processing in subsequent manufacturing steps. Ensuring uniformity at this stage is essential because variations in the size and shape of these pieces can lead to inconsistencies during wafer fabrication, affecting the overall quality and performance of the semiconductor devices they become part of.

Cropping also serves to remove any irregular edges or defects that might have been introduced during the block formation stage. By doing this, manufacturers can improve the yield of high-quality wafers, as only the best parts of the silicon blocks are taken forward for further processing. This step is also strategic for minimizing waste—by accurately sizing the pieces, the amount of silicon discarded during later stages can be reduced.

However, cropping is not without its challenges. It requires extremely precise machinery and skilled handling to ensure that each piece meets the stringent standards required for semiconductor manufacturing. The equipment used must be regularly maintained and calibrated to avoid any deviations that could compromise the integrity of the wafers.

Outer Diameter (OD) Grinding is a critical process in the manufacturing of silicon wafers, focusing on achieving the required thickness and a high-quality surface finish. This stage is essential for ensuring that the wafers are not only uniformly thin but also exhibit smooth surfaces, qualities that are crucial for the high precision required in semiconductor device fabrication.



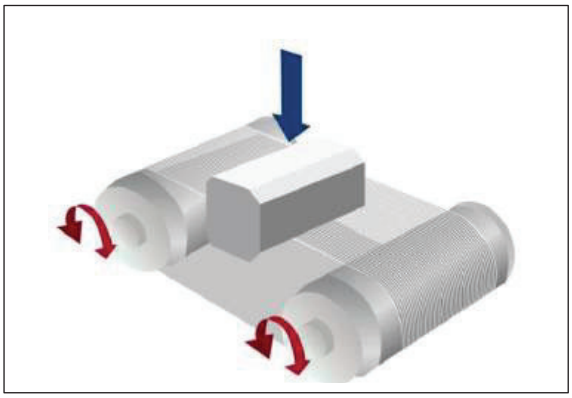
During OD grinding, the edges and outer surfaces of the wafers are meticulously ground to precise specifications using specialized grinding machines. These machines, equipped with diamond grinding wheels or other abrasive materials designed for silicon, carefully handle the wafers to avoid introducing any physical stress or damage that could lead to defects. The grinding process is meticulously controlled to achieve the exact thickness necessary for the functionality of semiconductor devices, as even minor deviations can affect the electrical properties.

A smooth surface is necessary to ensure good adhesion of thin films and other materials in subsequent processing steps such as deposition and etching. Surface irregularities can lead to defects in these layers, compromising the performance of the final semiconductor devices. OD grinding also shapes the edges of the wafers to specific profiles, important for handling and mounting the wafers in various equipment throughout the manufacturing process. Properly profiled edges reduce the risk of chipping and breakage, which are critical for maintaining the integrity of the wafers during processing.

The precision of OD grinding impacts not just the performance but also the yield of semiconductor manufacturing processes. The grinding must be carefully controlled to ensure that all wafers meet the stringent requirements for thickness and smoothness. This involves continuous monitoring and adjustment of the grinding parameters, including the speed of the grinding wheel, the pressure applied to the wafers, and the use of appropriate cooling or lubricating fluids to minimize thermal damage.

Moreover, the equipment used for OD grinding must be maintained at a high level of operational readiness. Regular calibration and maintenance are required to ensure that the grinding wheels are in good condition and that the machinery is capable of performing the necessary precise movements and adjustments.

Wafering is the process of slicing cropped silicon blocks into thin wafers, a critical step in the production of semiconductor devices. This stage uses advanced cutting technologies such as diamond wire saws or other precision cutting tools to achieve the required dimensions and properties of the silicon wafers. The quality of wafering directly influences the performance and reliability of the final semiconductor products, making it a highly controlled and precise operation.



The primary goal during wafering is to produce wafers that are not only thin but also have uniform thickness and exceptional flatness across their entire surface. These characteristics are vital because even minor deviations can lead to significant variations in the electrical properties of semiconductor devices. The process begins with mounting the silicon blocks onto the wafering machine. Here, either a single wire strung in a series of loops, known as a slurry saw, or a diamond-impregnated wire is used to cut the blocks into wafers.

Diamond wire saws, in particular, have become the preferred tool for wafering due to their ability to cut with high precision while minimizing material waste. The diamond-coated wire slices through the silicon with a controlled application of tension and speed, which helps maintain the integrity of the silicon crystals and avoids damage like cracks or chips.

Control over the wafering process is maintained through several critical parameters:

- *Speed of the wire:* Adjusting the speed can help control the rate of cutting and reduce thermal damage to the wafers.
- *Tension on the wire:* Proper tension ensures that the wire does not sag or break, which can affect the consistency of the cut.
- *Coolant flow:* The use of coolants not only reduces the heat generated during cutting but also helps in flushing away any debris, which could otherwise scratch the wafer surface.

After the wafers are sliced, they undergo inspection and cleaning. Any wafers that do not meet the stringent criteria for thickness and flatness are either reprocessed or discarded. This stage is crucial for ensuring that only the highest quality wafers proceed to the next phases of semiconductor manufacturing, such as doping, etching, and layer deposition.

The precision and efficiency of the wafering process also have a significant impact on the overall yield and cost-effectiveness of semiconductor production. Advances in wafering technology continue to focus on increasing the throughput and reducing the kerf loss (the width of material removed during the cutting process), which helps maximize the number of wafers produced from each silicon block.

Wire saws provide the most accurate cutting with the least amount of surface damage and chipping of material.

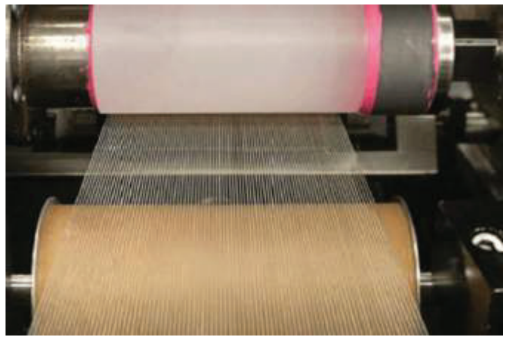
Today wire sawing is preferred by majority of solar silicon manufacturers over other technologies/cutting methods. Wire saw operates similarly to horizontal hack saw, where head containing a pack of blades lengths of plain edge stainless or spring steel mounted parallel to head travel oscillates back and forth over the work piece or pieces which are mounted on a bed. The bed can be fed up into the blades at selected pressures. A series of nozzles apply a flow of abrasive slurry (grains of silicon carbide or other abrasive in a liquid vehicle.

That provide a cutting or lapping action between the blades and material. The wire saw allows slicing of hundreds of wafers simultaneously with the same continuous wire. For the most part today abrasives are used and preferred over diamond for cutting silicon.

Although use of wire bonded with diamond offers many advantages in terms of faster cutting speed (frequently triple the speed) and improved surface finish quality (less secondary operations such as polishing). Due to the pullouts of diamond crystals/particles, the cutting life is short and costly for high production scenario.

For this reason, most silicon manufacturers utilize copper plated piano wires designed to trap abrasive particles (such as alumina or SiC) suspended in mechanical oil or water based coolant. To provide the cutting action and lubrication of the moving wire. The wire diameter frequently used is smaller than 0.15mm and cutting kerf is about 0.19mm and 0.15mm and smaller. Abrasive slurry grit size varies from 1000 to 250 grit. Viscosity and continuous mixing of the slurry must be maintained in order to produces consistent results.

Wire is would around 2, 3,or 4 grooved mandrels in order to allow multiple loops for simultaneous slicing of the same ingot. When the looped wire is running across the ingot, the abrasive particles impeded the soft surface of the piano wire will slowly lap/grind off silicon on micro level (bit by bit). The cutting action is done by reciprocating motion. The wire is used once, and replaced with a new roll.



Typically this type of wire saw can travel at surface speed of 6 mm/sec. The wire moves forward for abut 300mm and this is retraced for abut 200mm. Net advance of the new wire is at an average speed of 2 m/sec with about 100 m new wire passed through each cycle. The wire can run continuously for more than 300 km long. More than 500 slices can be sawn simultaneously. In a production environment 8" (200mm) silicon boul in leas than 8 hours and 12" (300mm) boul in less than 12 hours.

Chamfering is a vital step in the manufacturing of silicon wafers, serving as a critical measure to enhance the durability and handling resilience of the wafers. This process involves beveling the edges of the wafers, which helps to prevent chipping and breakage during subsequent handling and processing steps. Chamfering not only increases the mechanical strength of the wafers but also significantly reduces the risk of damage that can occur from routine handling or when the wafers undergo various semiconductor fabrication processes.

The chamfering process is executed using specialized equipment that precisely grinds the edges of the wafers to create a beveled profile. This beveling is typically done at a 45-degree angle, although the exact angle and width of the chamfer can vary depending on the specifications required for particular applications. The goal is to remove any sharp edges and to create a uniform, smooth perimeter that can withstand stress without fracturing.

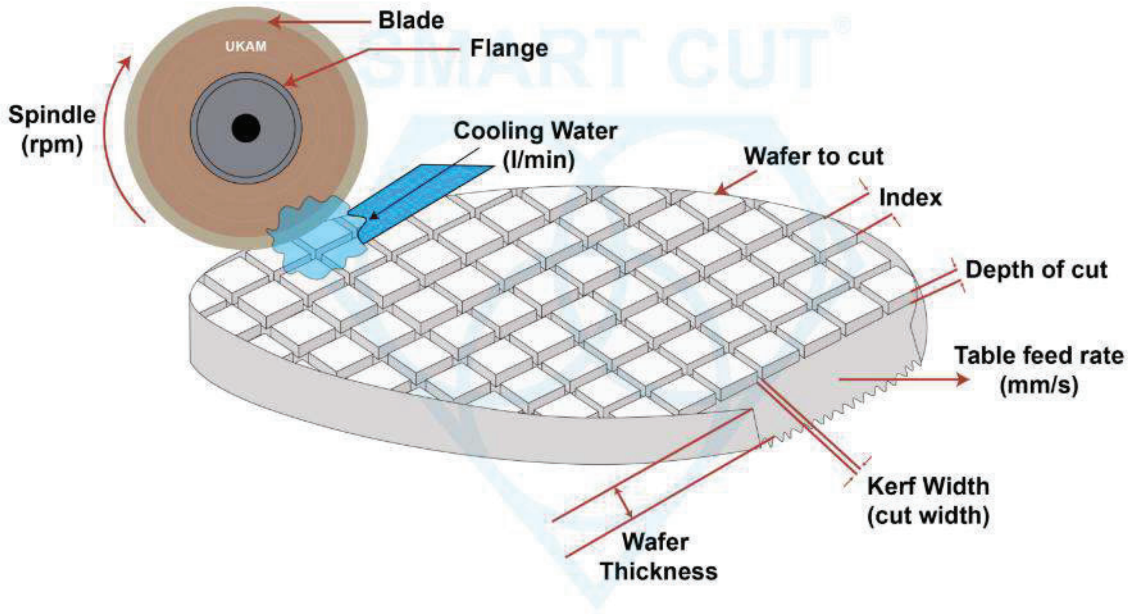
Several techniques are employed for chamfering, including:

- *Mechanical Grinding:* This is the most common method, where mechanical grinders equipped with diamond-tipped wheels are used to shave off the sharp edges of the wafers. This method is highly effective and can be adjusted for different chamfer sizes.
- *Laser Chamfering:* For applications requiring high precision and minimal physical contact, laser chamfering can be used. This method involves using a focused laser beam to melt and reshape the wafer's edge. It's particularly useful for very thin or delicate wafers where mechanical stress needs to be minimized.
- *Chemical Etching:* In some cases, chemical etching processes are used to chamfer the edges. This involves exposing the wafer edges to chemical agents that selectively remove material, rounding off the edges. This method is less common but can be advantageous for certain types of semiconductor materials.

Chamfering not only enhances the structural integrity of the wafers but also plays a significant role in improving the overall yield of the semiconductor manufacturing process. Wafers with chamfered edges are less likely to cause cross-contamination with debris from chips or cracks, thereby maintaining the cleanliness and purity required in semiconductor environments.

Dicing (as an optional enhancement and value added revenue stream) is a crucial step in the fabrication of semiconductor devices, where a full silicon wafer is segmented into individual chips, also known as die. This process must be precisely controlled to ensure that the integrity and functionality of each die are maintained. The choice of dicing blades and techniques significantly impacts the quality, efficiency, and cost of semiconductor production.

Resin bond blades are commonly used because they provide smooth cuts with minimal chipping, thanks to their diamond abrasives held together by a resin binder. The flexibility of the resin bond allows for high-speed cutting with reduced mechanical stress on the wafer, ideal for materials sensitive to cracking and chipping. Sintered nickel bond blades, made by sintering diamond particles in a metal matrix, typically nickel, are extremely durable and maintain a sharp cutting edge over extended periods. These blades are useful for high-volume production where longevity and consistent cutting depths are critical.



Various dicing techniques are employed depending on the material of the wafer and the desired outcomes. Blade dicing, the most common method, involves a rotating diamond-coated blade cutting through the wafer and is preferred for its speed and efficiency in high-volume settings. Stealth dicing, a newer technique, uses a laser to create a modified layer within the wafer, allowing it to be broken apart with minimal physical stress and is advantageous for very thin or brittle materials. Laser dicing, which uses lasers to cut the wafer, offers high precision and flexibility in cutting paths and is useful for complex shapes or when minimal damage to the surrounding material is critical.

Dicing silicon wafers presents several challenges, including kerf loss—the width of the cut made by the blade—which results in material loss. Minimizing kerf width is crucial to maximizing the number of dies per wafer. Both blade and laser dicing can generate significant heat, which may cause damage to the die or affect its properties. Managing heat through optimal blade speed and coolant use, or by adjusting laser parameters, is essential. Mechanical stresses during dicing can lead to chip edges chipping off or entire dies cracking. Using appropriate blade types and cutting parameters is key to minimizing these defects.